



The Columbia Accident: Synopsis of CAIB Report* Regarding the Physical Cause of the Accident and and Personal Thoughts

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***Seminar based on CAIB Appendix F2, Vol IV
by J. O. Arnold, H. E. Goldstein and D. J. Rigali**

September 27, 2011

The Board



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Dr. James N. Hallock, Chief, Aviation Safety Division, Department of Transportation, Volpe Center

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Admiral Harold Gehman, Admiral, US Navy (retired) - Chairman

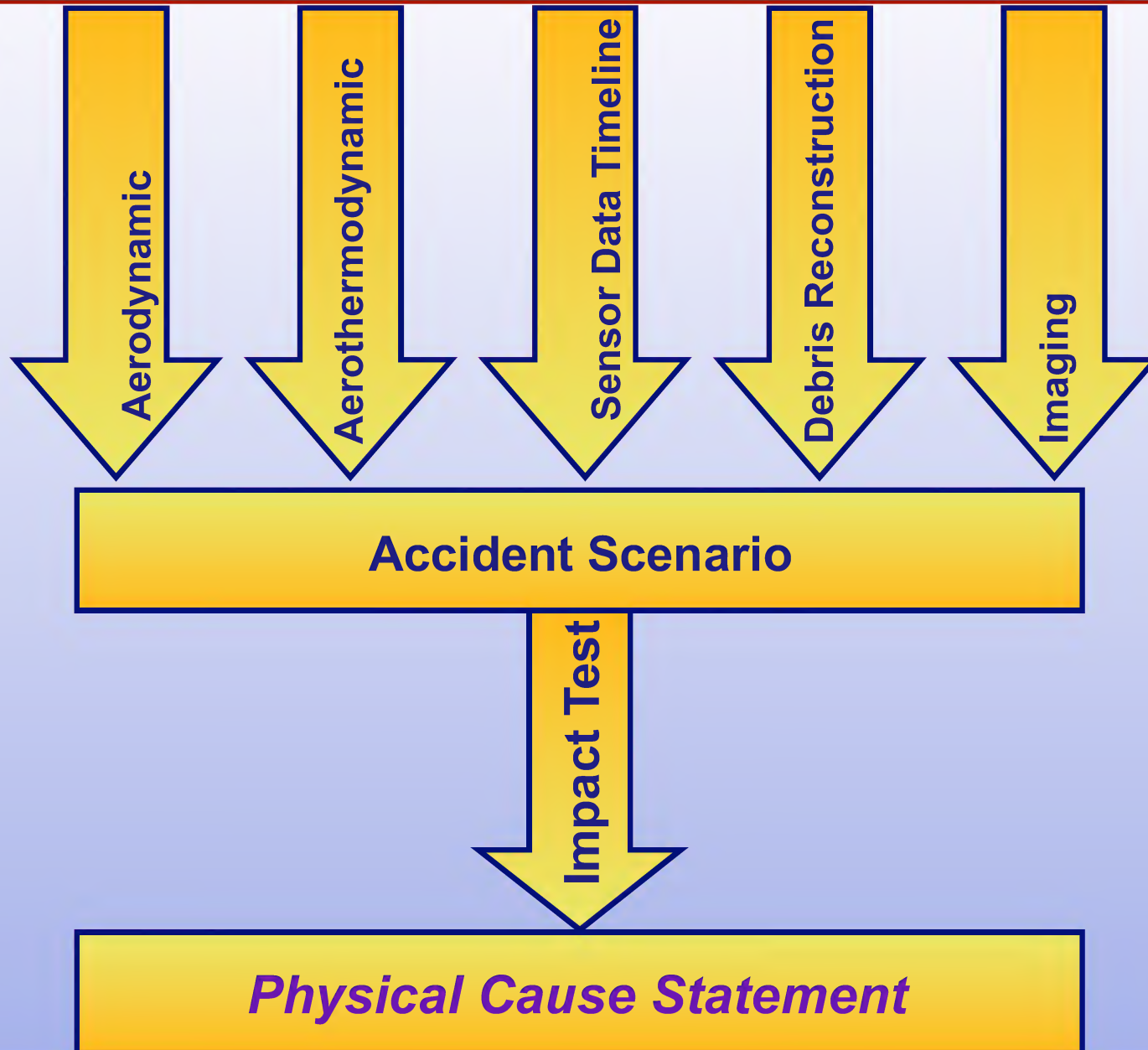
Mr. Steven B. Wallace, Director of Accident Investigation, Federal Aviation Administration

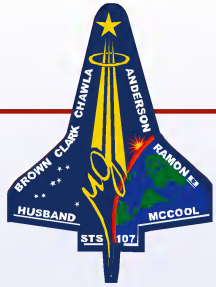
Dr. John Logsdon, Director of the Space Policy Institute, George Washington University

Dr. Sheila Widnall, Professor of Aeronautics and Astronautics and Engineering Systems, MIT



Physical Cause





Assignment: “Follow the TPS”

- Confirm or Refute: “During the launch of STS 107, a briefcase-sized piece of foam from the External Tank struck the Reinforced Carbon-Carbon (RCC) Left Wing Leading edge of Shuttle Columbia compromising the RCC. During entry, the damage to the RCC led to the structural failure of the wing, the tragic loss of Columbia and the STS 107 crew”
- This was the first, obvious loss of any U.S. vehicle during hypervelocity atmospheric entry, greatly complicating the investigation.
- CAIB board member, G. Scott Hubbard assigned the “Follow the TPS” task to J. O. Arnold, H.E. Goldstein and D. J. Rigali on February 6, 2003, less than a week after the accident. The results were published in August, 2003.



What did we know early in the investigation?

- Combined background in aerothermodynamics, Shuttle tiles and carbon-carbon
- Knowledge that superheated shock layer gases had entered the left wing box, very probably melting the aluminum substructure, and in essence, sawing the left wing off from the inside-out.
- Very poor quality imagery of the foam strike - no underside view
- Amateur video of entry from California coastline to Texas, including the Starfire photograph taken in New Mexico
- NASA data tracking, but No Orbiter Experiments (OEX) on-board engineering data - this was stored on board on magnetic tape and subsequently was recovered.

Frame 4912

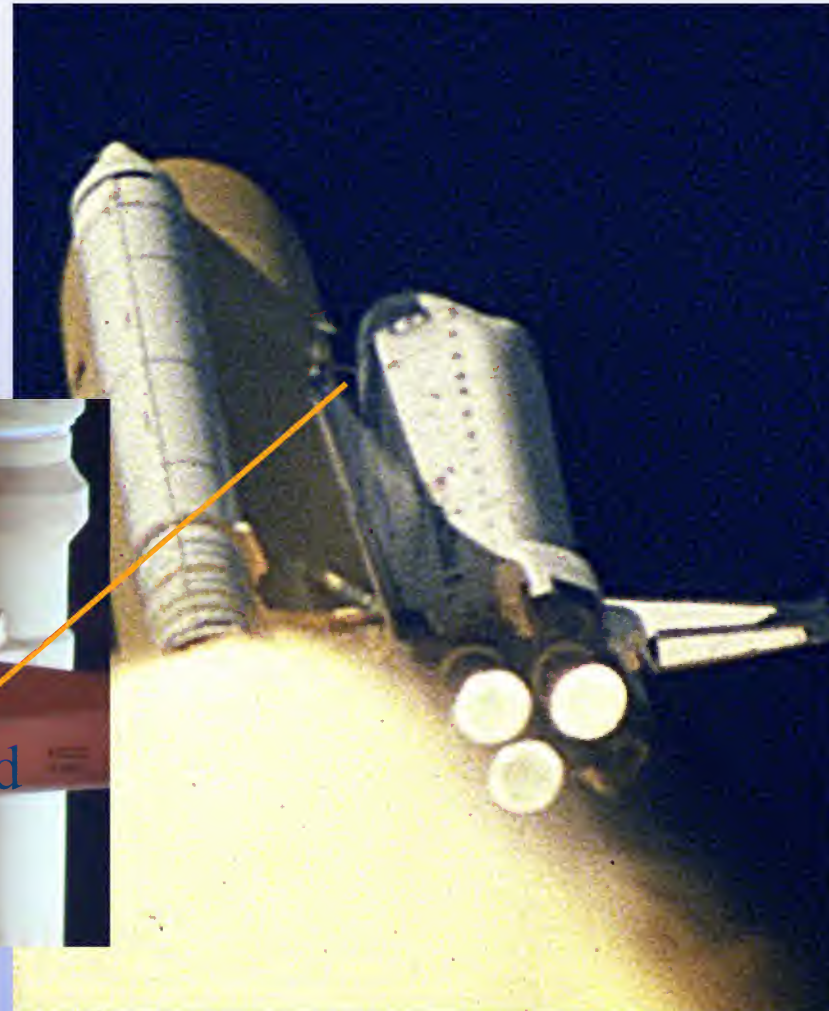




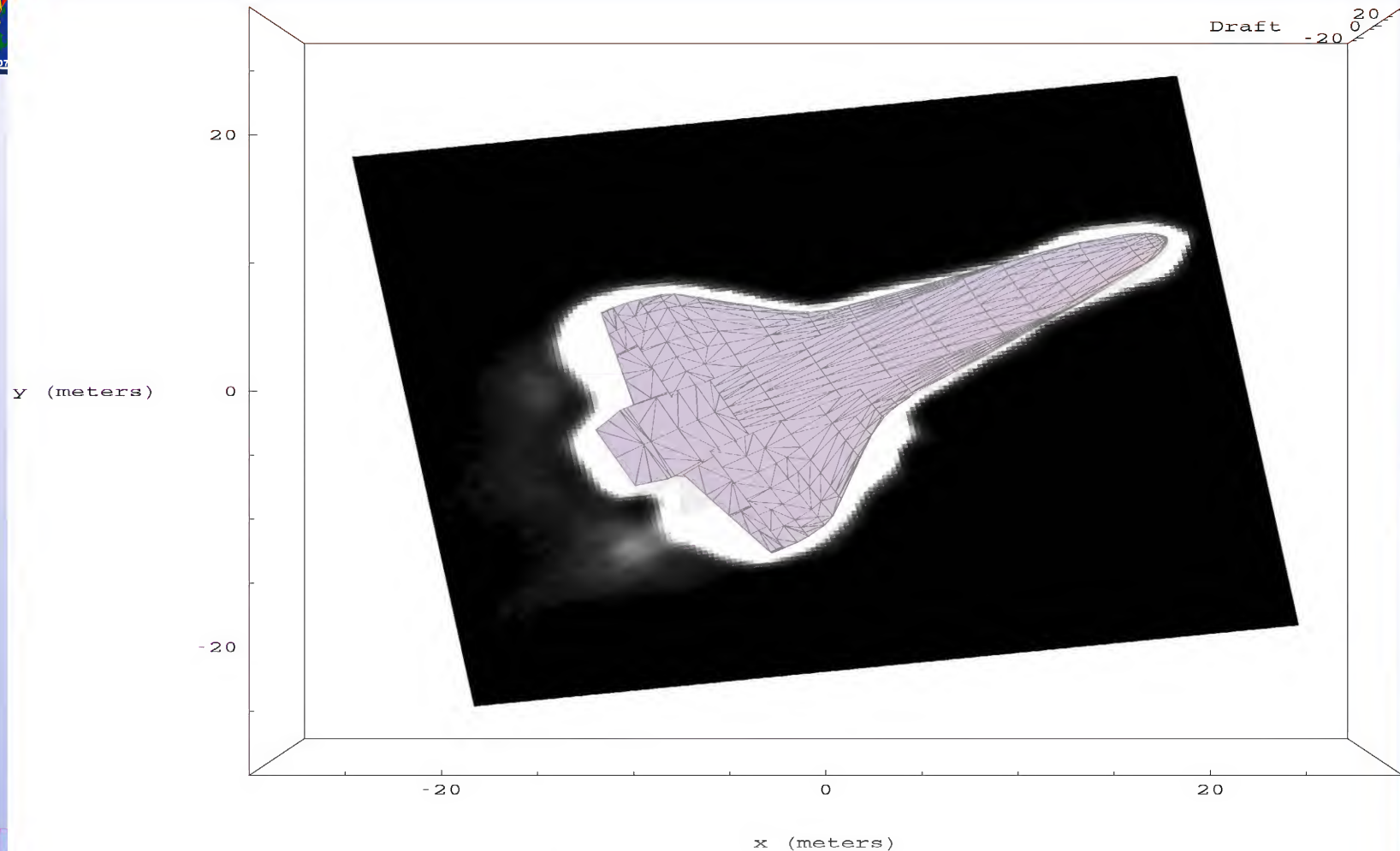
Bi-Pod Ramps



Bi-Pod



Starfire Photo from Kirtland AFB GMT13:57:14



Starfire Optical Range Image (26 March 2003)
model overlay (R. Cleis, R. Fugate, R. Johnson)
image sharpened using deconvolution (J. Christou)

The model scaling and orientation are based on telemetry (latitude, longitude, and altitude from NASA) and observations (azimuth, elevation, and range from SOR). The image scaling and orientation were derived from measurements using star fields. The Columbia model was provided by NASA.



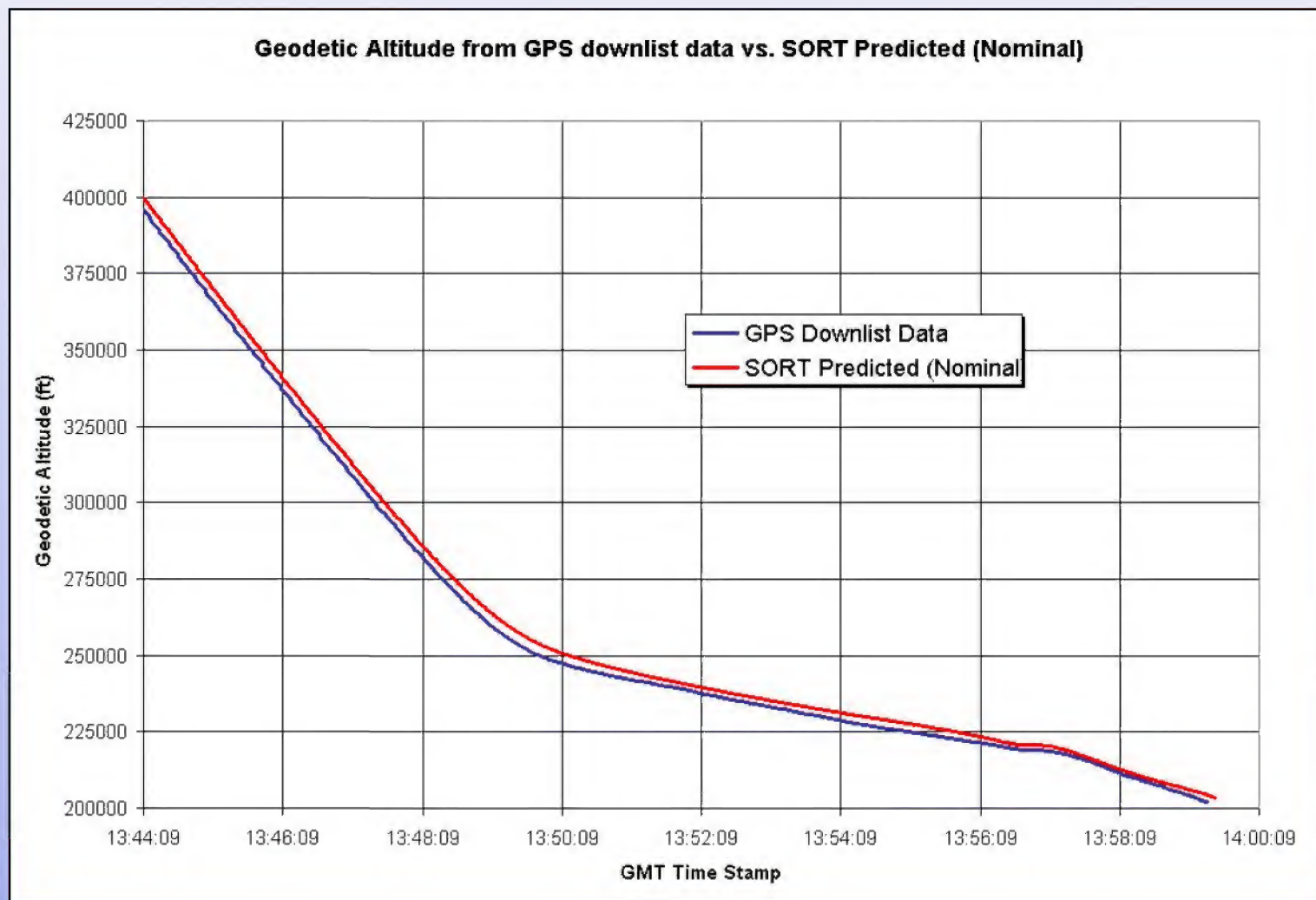
Background: Shuttle Aerothermodynamics & TPS

- Entry Trajectory
 - Normalized aerothermodynamic entry heating profile
 - Zoom-in on wing leading edge
- Space Shuttle Thermal Protection System
- Huge, national efforts in CFD, Thermal Analysis, Aero, etc started soon after the accident, led by NASA JSC



Entry trajectory

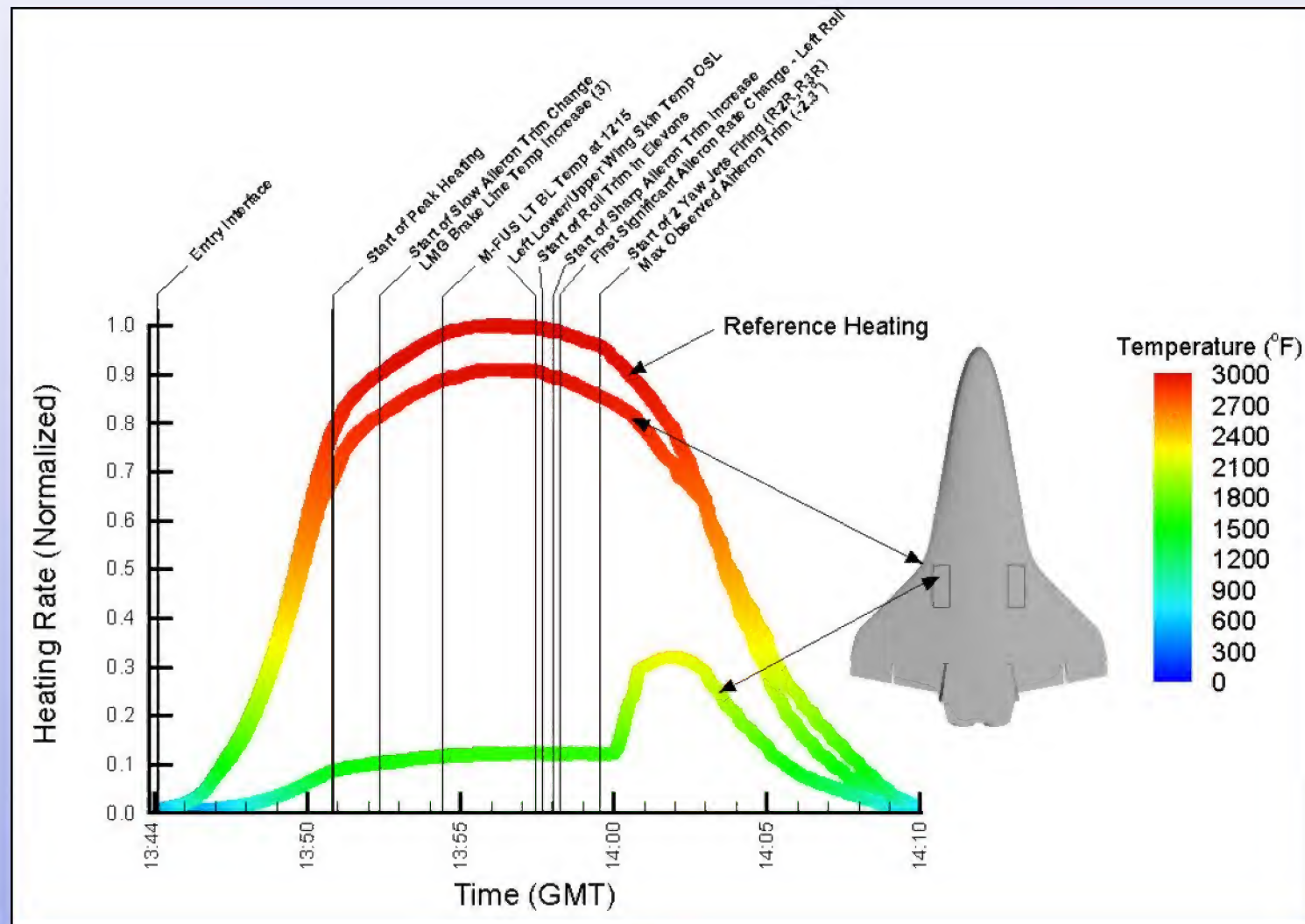
Figure 1 (a) Normal entry; Geodetic Altitude Vs
GMT Entry Interface EI
at 400,000 ft/ Mach 24. Angle of attack 40 degrees



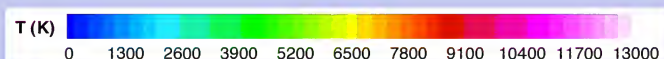
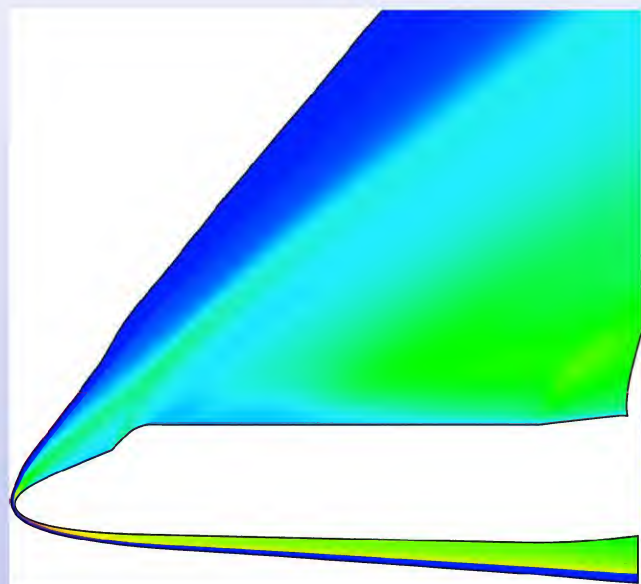
Entry heating



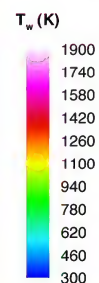
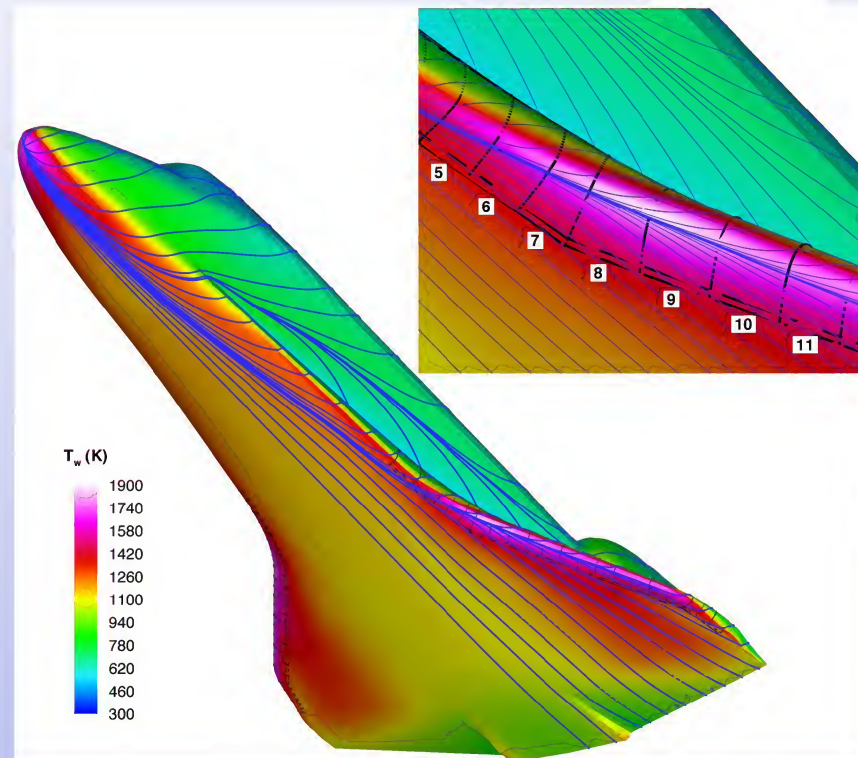
Figure 1 (b) Normal entry; Normalized Heating Rates Vs
GMT Entry Interface EI
at 400,000 ft/ Mach 24. Angle of attack 40 degrees



Space Shuttle - Bow shock layer and surface temperatures*



Gas Temperatures from CFD Solution
Pitch plane, Near Peak Heating.
Angle of attack: 40 degrees,
246,000 ft altitude, Mach 22.91 at 13:50:53



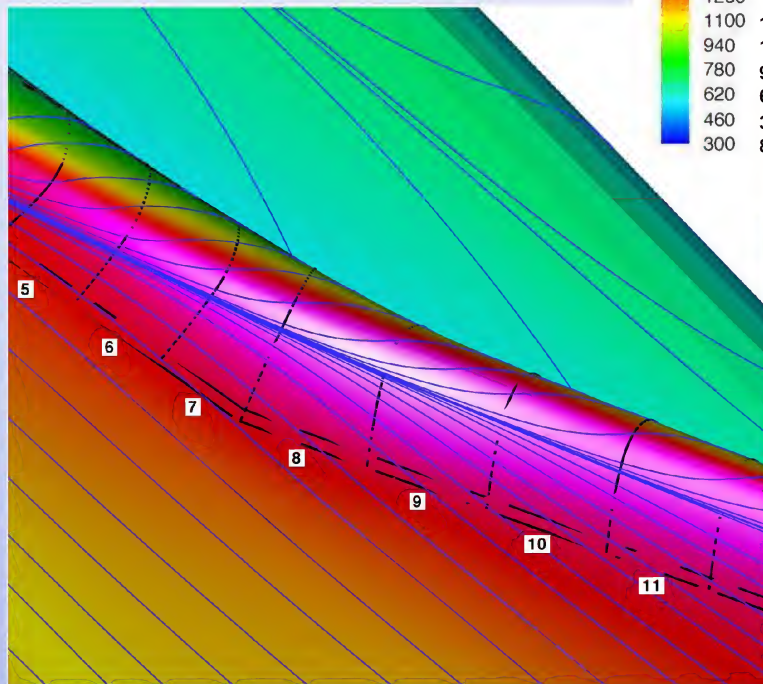
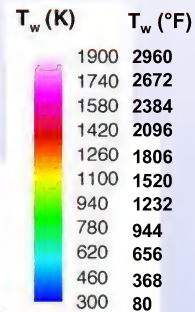
Surface Temperatures from CFD Solution
Near Peak Heating.
Angle of attack: 40 degrees,
246,000 ft altitude, Mach 22.91 at 13:50:53

*CFD By NASA Ames, J. Brown, R. McDaniel and D. Prabhu

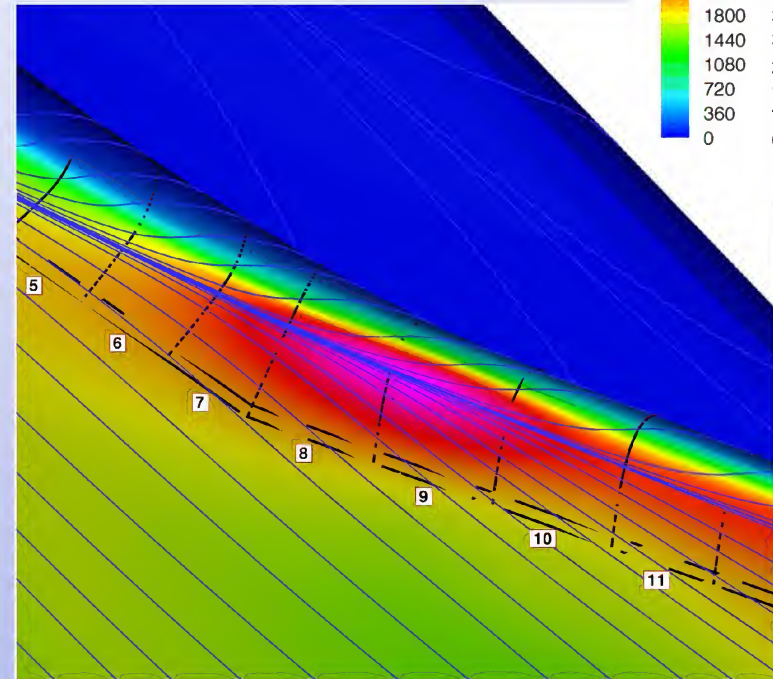
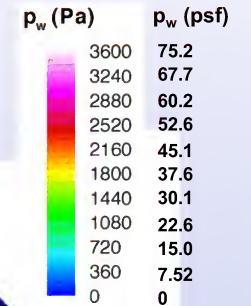


CFD Solutions for wing leading edge

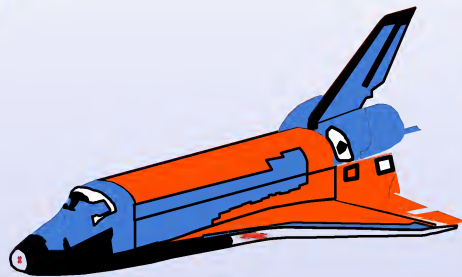
Surface Temperature



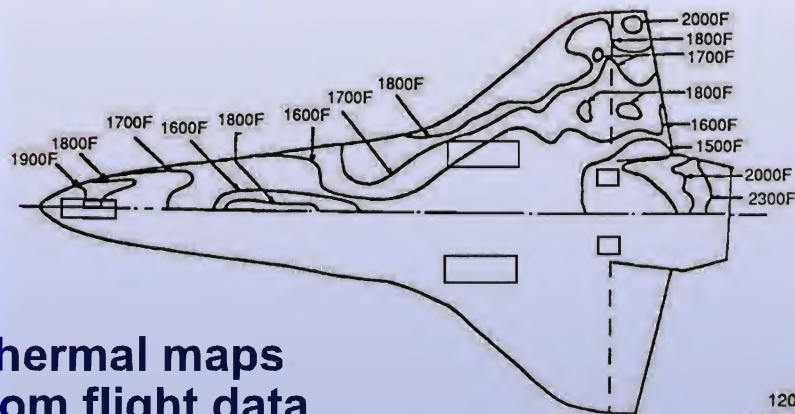
Surface Pressure



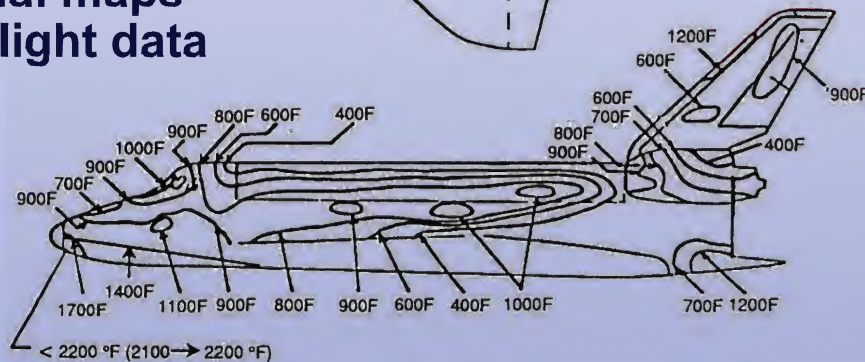
Overview of Space Shuttle TPS



RCC
 HRSI Tile
 LRSI Tile
 AFRSI
 FRSI



**Thermal maps
from flight data**

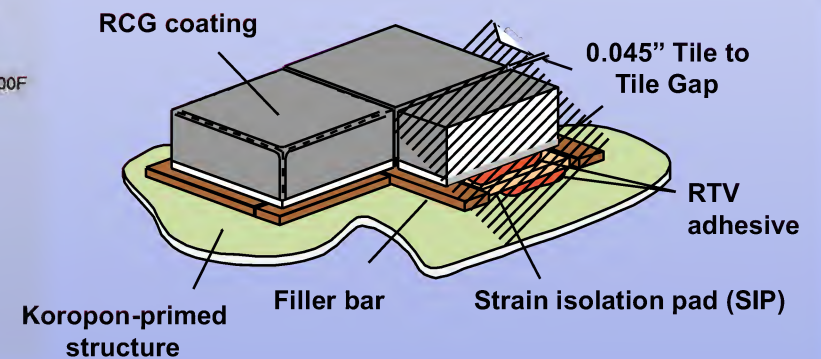


RCC leading edge system



HRSI tile system

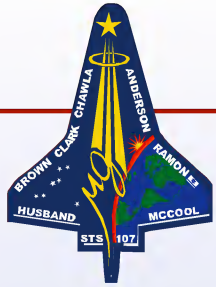
- LI-900
 - LI-2200
 - FRCI-12
- Multi-use
Temperature < 2300 F



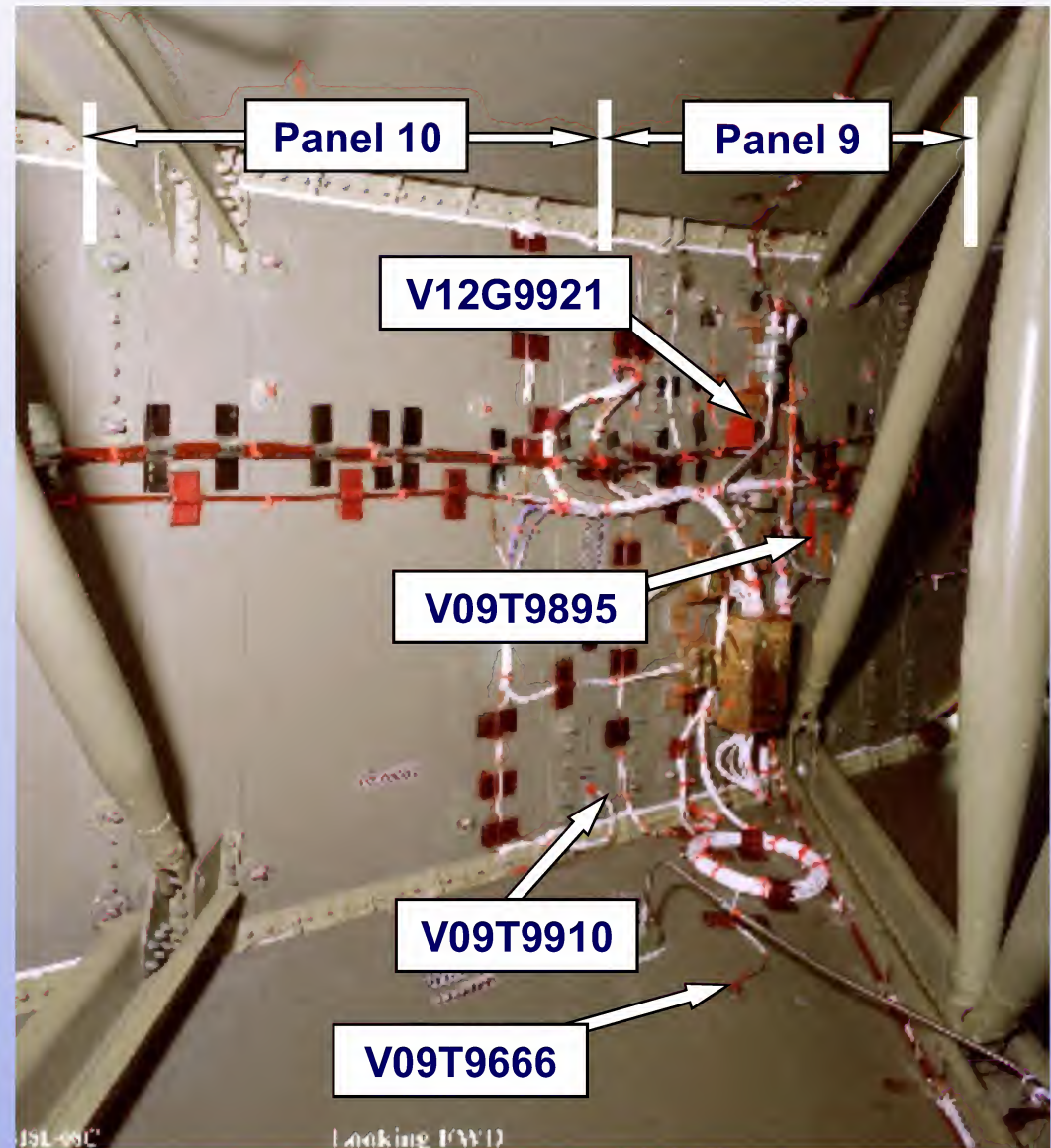


Orbiter Experiments (OEX) sensors and data

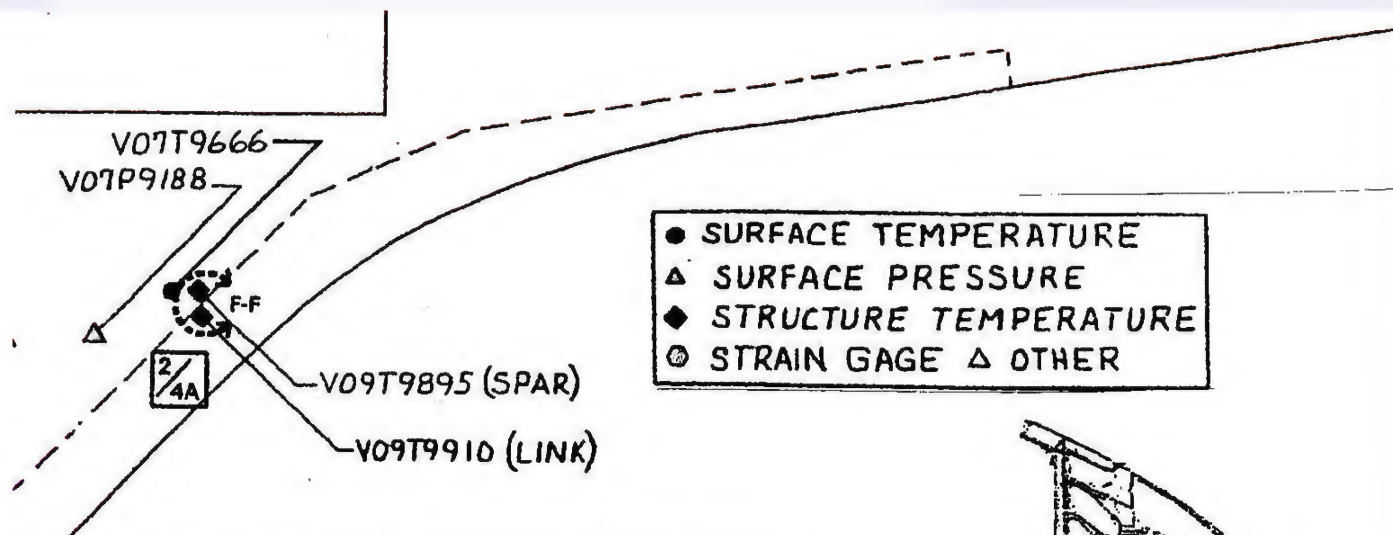
- Key Sensors and their locations on the orbiter. Shuttle Columbia was the only vehicle fitted with OEX sensors.
- Out-family sensor readings for STS 107. Tape recorder was recovered from the debris field. By a miracle, the tape was OK.
- Time-line of sensor readings and interpretation



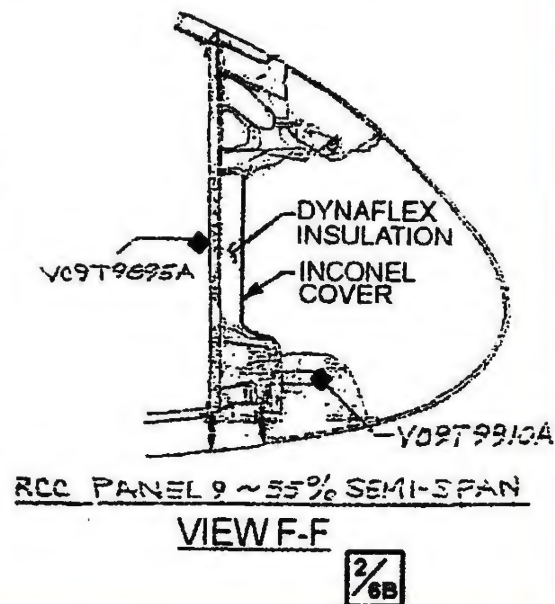
OEX Sensors, inside wing, behind spar



OEX sensor locations

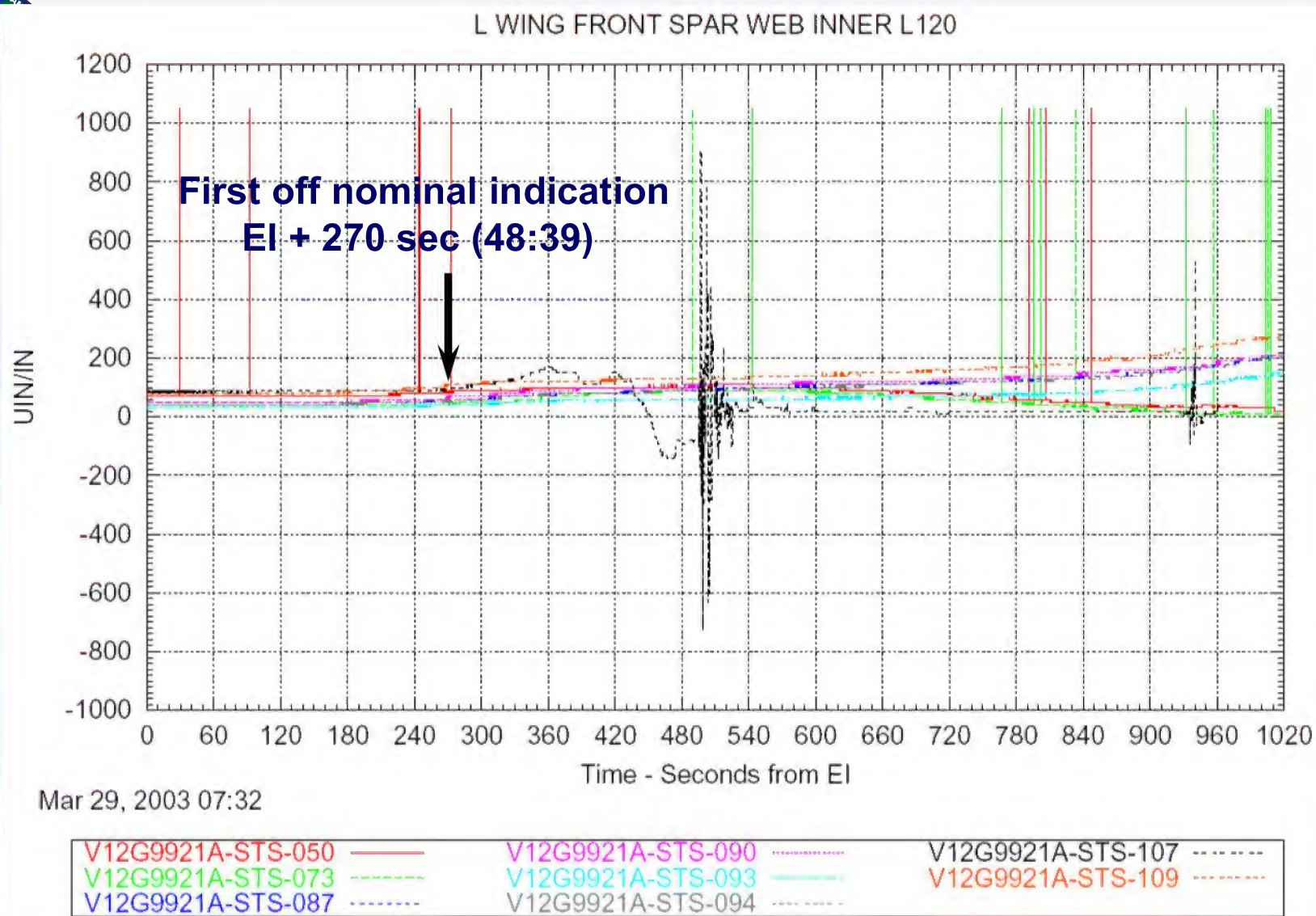


SIGNATURES		DATE	DESCRIPTION	MATERIAL	SPECIFICATION
DR J.A. SMITH		2-89	NATIONAL AERONAUTICS & SPACE ADMINISTRATION LYNDON B. JOHNSON SPACE CENTER HOUSTON, TEX.		
ENG			LOWER SURFACE PRESSURES, TEMPERATURES, AND MID FUSELAGE STRAINS		
CH					
APP J.A. SMITH		2-89			
AUTH					
REVISED JUNE 23, 1989			CODE IDENT NO.	SIZE	DWG NO.
				D	JSC-ES3-33189
			SCALE	SHEET 2 OF 6	



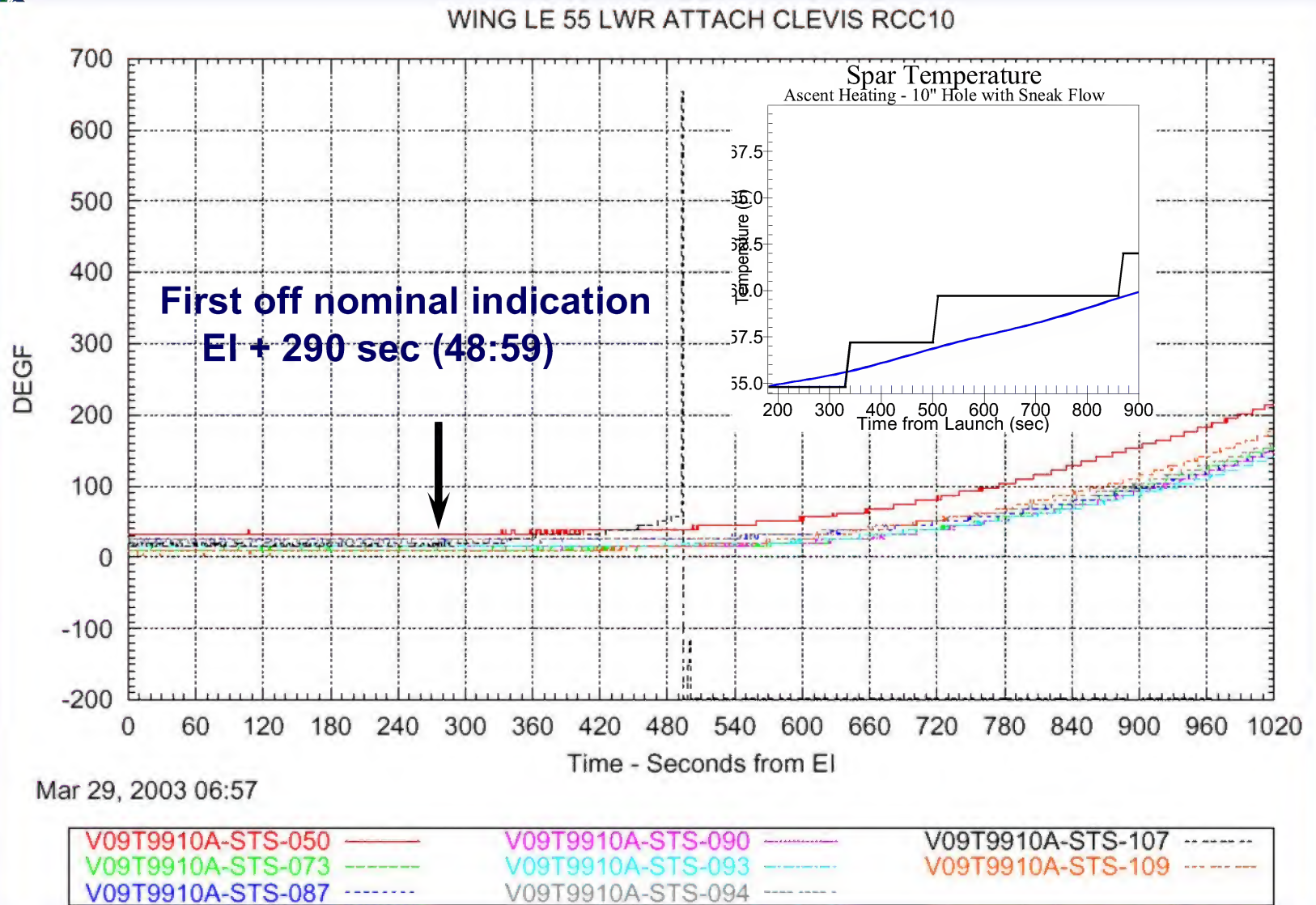


OEX STS-107 Flight Data



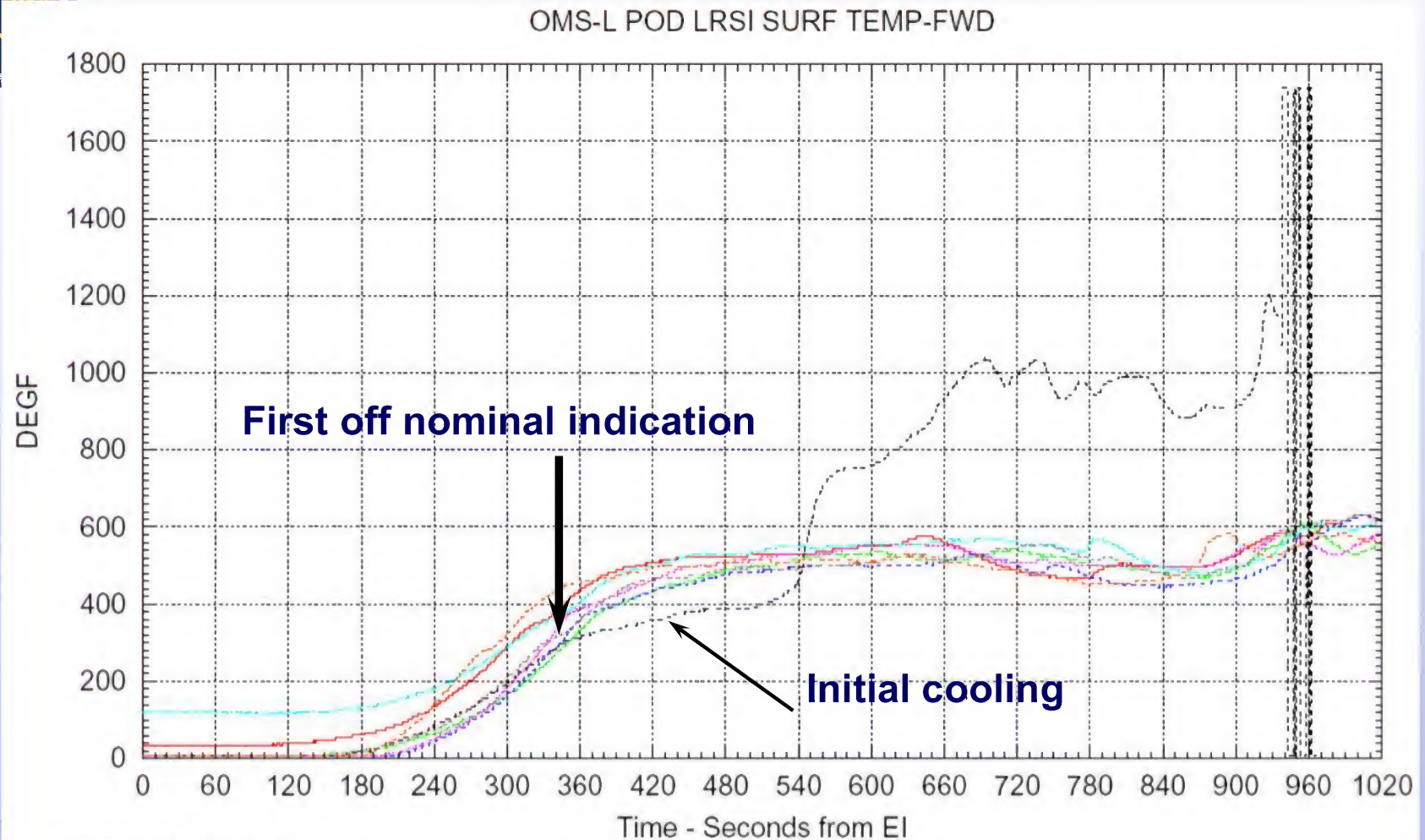


OEX STS-107 Flight Data and Thermal Analysis by JSC/C. Madden



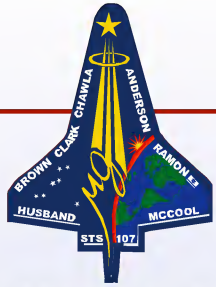


“Typical” Off Nominal OMS Pod Temps.



Mar 29, 2003 06:53

V07T9220A-STIS-050	V07T9220A-STIS-090	V07T9220A-STIS-107
V07T9220A-STIS-073	V07T9220A-STIS-093	V07T9220A-STIS-109
V07T9220A-STIS-087	V07T9220A-STIS-094	

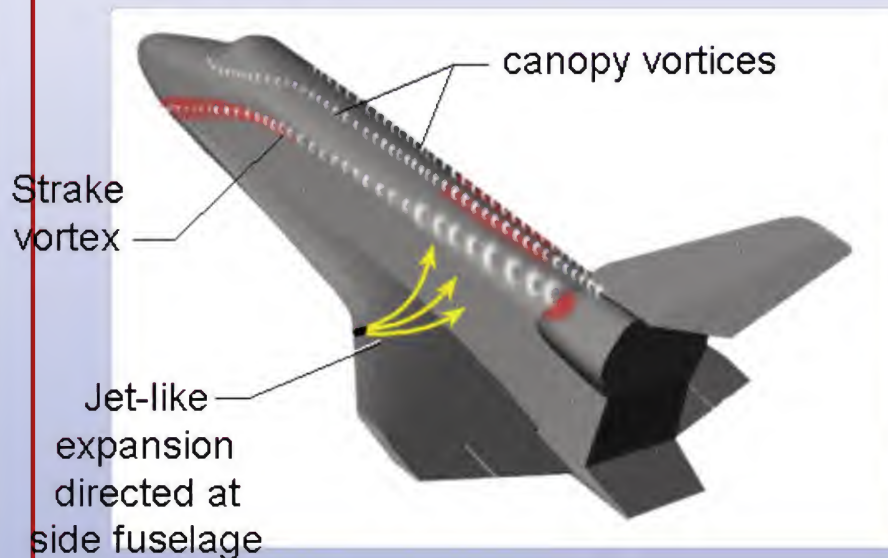


LaRC Wind Tunnel Tests Data help explain cooling trends on OMS pod

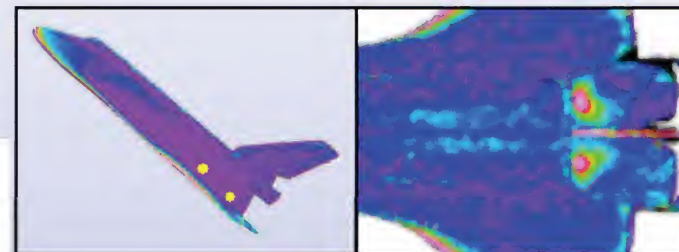
Effect of Missing RCC Panel on Orbiter Leeside Flowfield as Inferred From Surface Heating Patterns

Mach 6 Air $\gamma_{\text{eff}} = 1.4$ $\alpha = 40$ deg $Re_{\infty, L} = 2.4 \times 10^6$ $\beta = 0$ deg

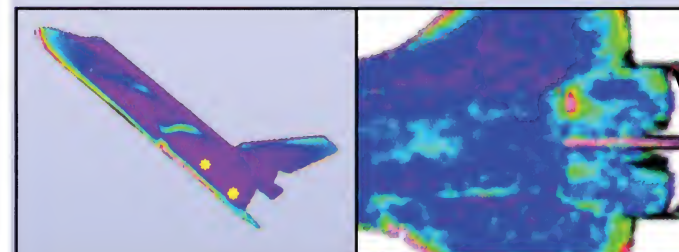
Conceptual sketch of Orbiter leeside flowfield



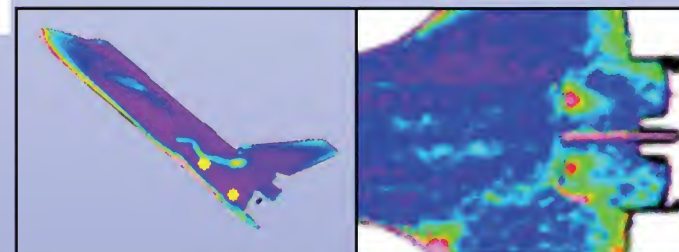
Wing leading edge damage influences leeside flowfield



Baseline



Missing panel #5



Missing panel #10

Note cooling trend on left OMS pod

13:44 13:45 13:46 13:47 13:48 13:49 13:50 13:51 13:52 13:53 13:54 13:55 13:56 13:57 13:58 13:59 14:00 14:01

El 1st Temp 1st OSL Debris 1-15 LOS

47:00

48:00

49:00

50:00

Timeline Events

Q = 2 psf
Aero Active

L -Wing (RCC9) LE spar
strain starts O/N Inc

L -Wing RCC9/10 Clevis
temp starts O/N Inc

4-OMS pod Surface
Temps Start O/N Inc

Entry Heating Continues

WLE Temp >1500°

WLE Temp >2000°

WLE Temp >2500°

48:39 (EI+270 seconds) RCC panel 9 spar insulator strain gage (V12G9921) shows off nominal increase. Thermal stresses build due to the breach in the wing and hot gas impingement on the spar. Pressure also starts to build in the RCC wing cavity adding to the load on the spar. All these loads combine and put an off nominal strain on the spar. Fig. 10

48:59 (EI+290 seconds) Hot gas continues to flow into the RCC cavity through the damaged RCC panel 8. Heat entering RCC cavity is first registered by the temp sensor (RTD) on RCC panel 9/10 clevis fitting (V09T9910). Fig. 11

49:49 (EI+340 seconds) OMS pod temperatures initially become cooler than nominal due to leading edge RCC panel damage, as confirmed by LaRC wind tunnel tests. Figs 12 and 13

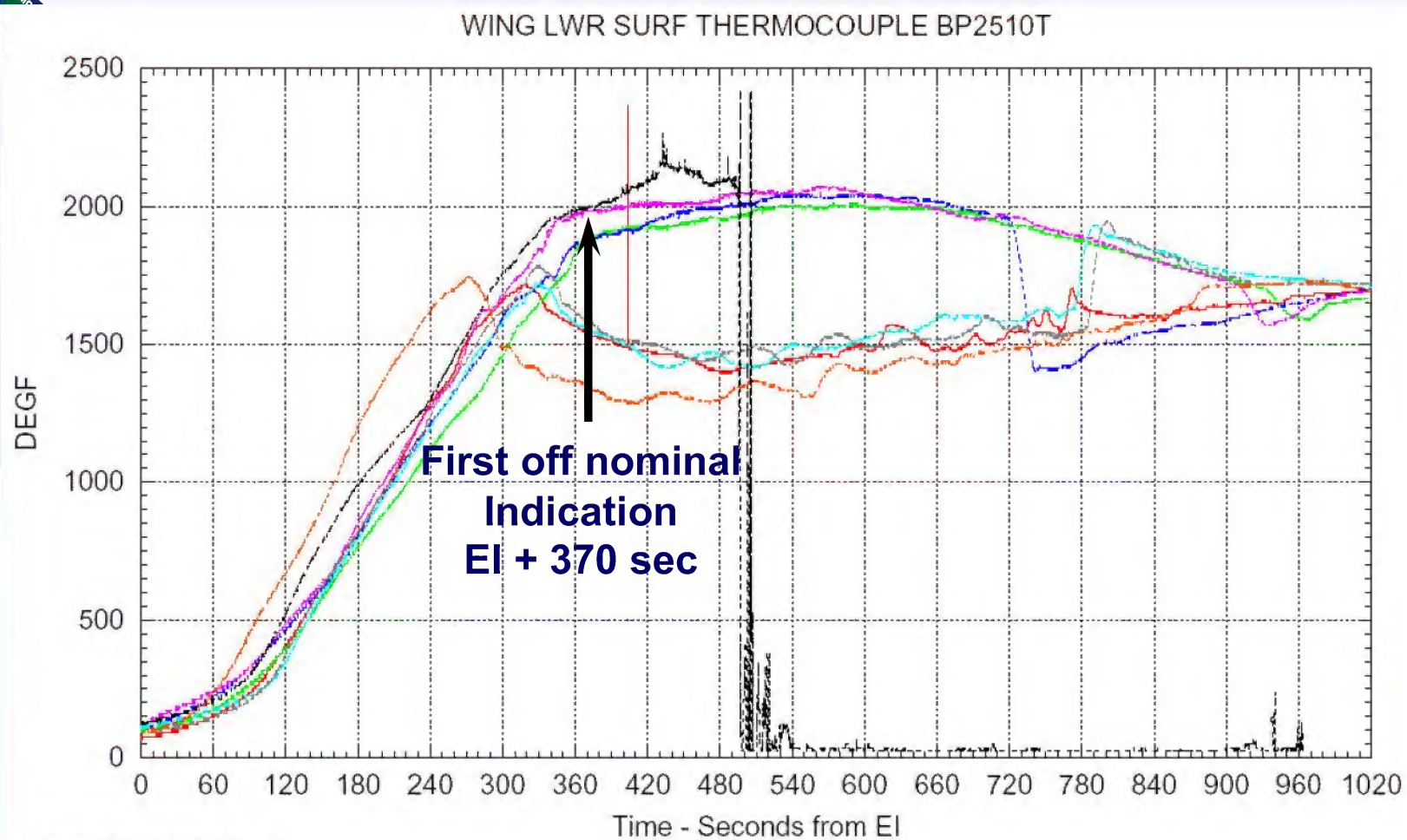
Scenario



More OEX data and interpretation



OEX/MADS STS-107 Flight Data



Mar 29, 2003 06:55

V07T9666A-STIS-050	—	V07T9666A-STIS-090	---	V07T9666A-STIS-107	----
V07T9666A-STIS-073	---	V07T9666A-STIS-093	----	V07T9666A-STIS-109	-----
V07T9666A-STIS-087	-----	V07T9666A-STIS-094	-----		



NASA Langley/(Gnoffo) Orbiter Surface Streamlines EI+404; Mach=24.9; Alt.=243k ft

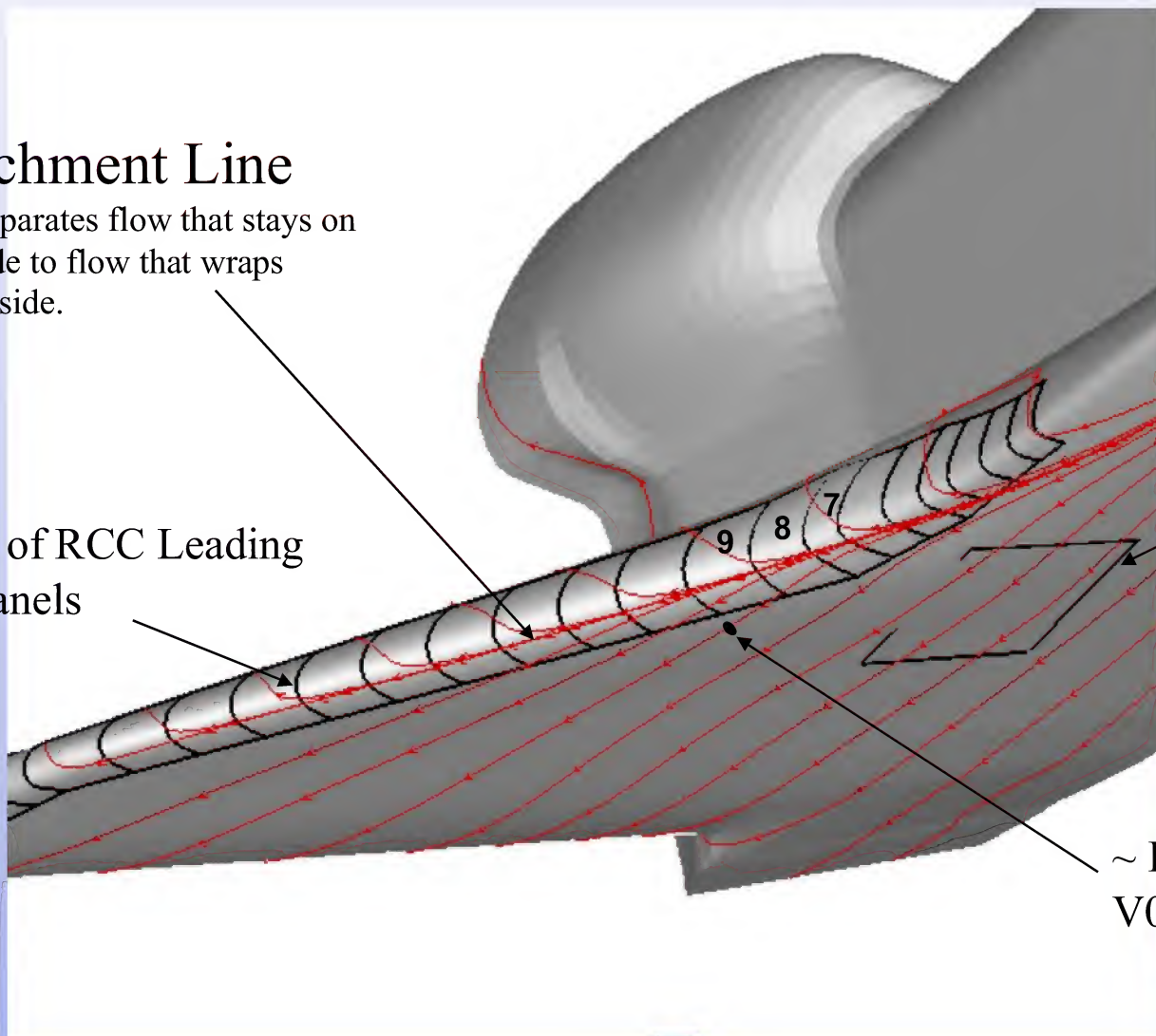
Attachment Line

- Line that separates flow that stays on windward side to flow that wraps around to leeward side.

Outline of RCC Leading Edge Panels

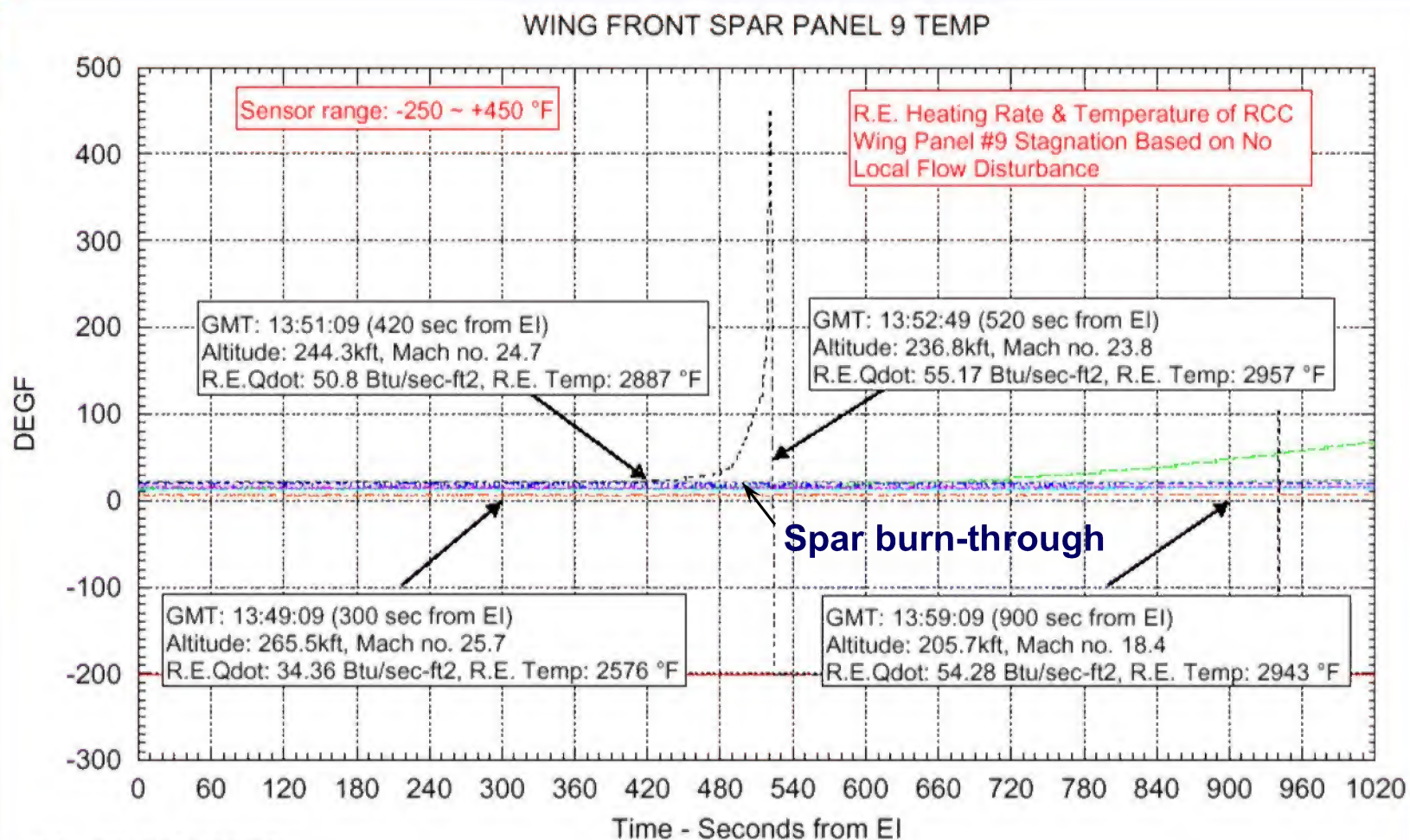
Outline of Main Landing Gear Door

~ Location of V07T9666A





OEX/MADS STS-107 Flight Data



Mar 29, 2003 06:57

V09T9895A-ST5-050	V09T9895A-ST5-090	V09T9895A-ST5-107
V09T9895A-ST5-073	V09T9895A-ST5-093	V09T9895A-ST5-109
V09T9895A-ST5-087	V09T9895A-ST5-094	

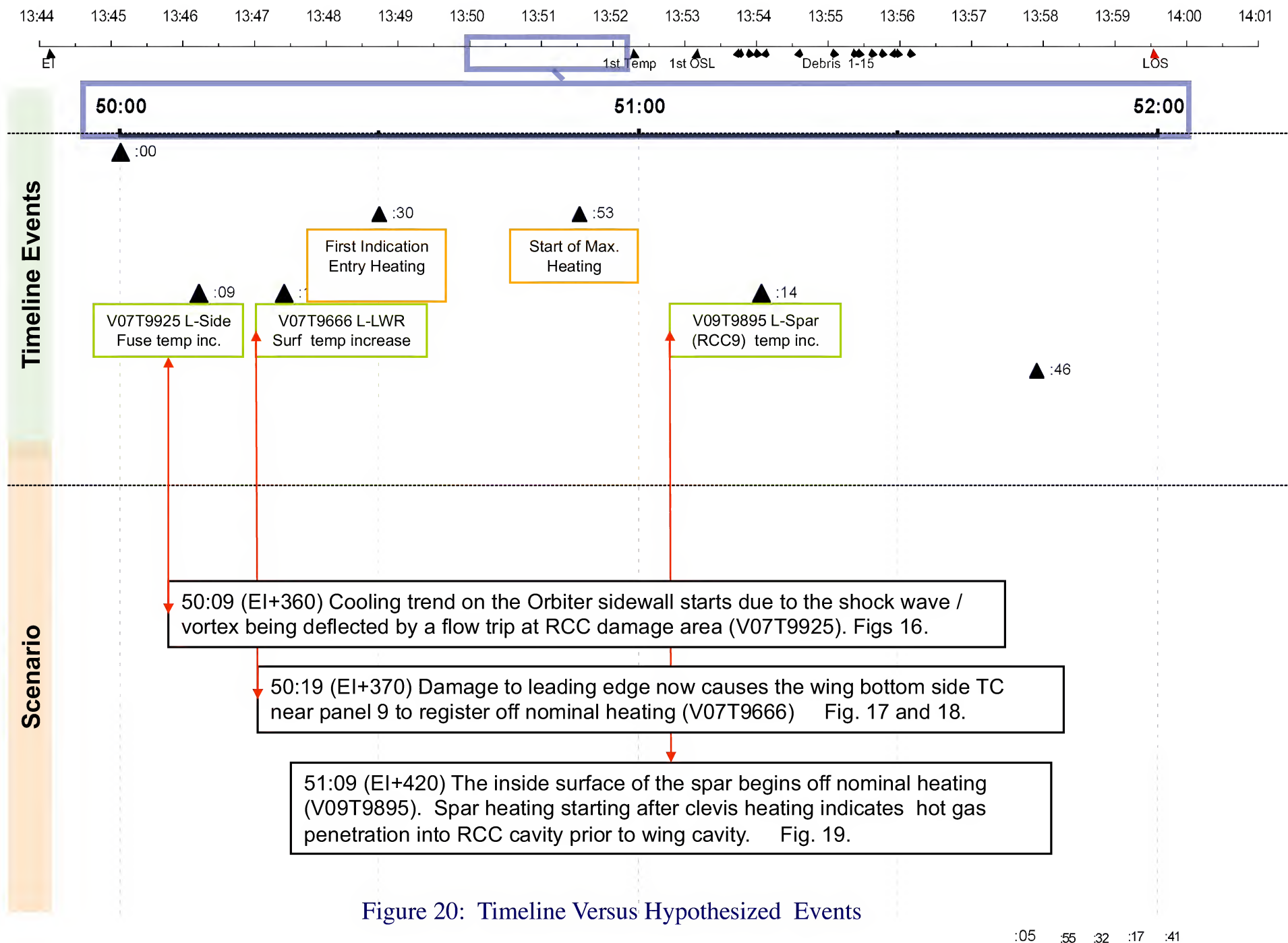


Figure 20: Timeline Versus Hypothesized Events



Analysis of the Columbia Debris

- Huge effort start & ongoing to recover debris from the field
- Huge effort at KSC to identify parts
- CAIB, NASA and Contractor teams conducting forensics at KSC



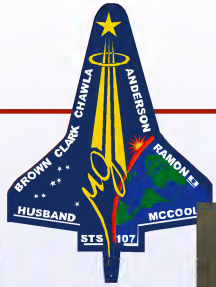


Reconstructed RCC Panel 8/9 Area



Probable Initial Breach in Panel 8





Close up of lower edge of panel 8/9

Outside of thermal
barrier slot

LI 2200 Carrier
Panel Tile





Foam Impact Testing

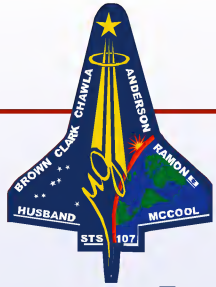
- CAIB lead: G. Scott Hubbard. Paul Wilde (CAIB) was lead on “Follow the Foam”. Large modeling effort led by JSC NASA and included work by Sandia
- Tests on tiles conducted first, little damage
- Then tests on fiberglass simulating RCC
- Tests on actual, aged RCC in one-for-one ground test
- Conclusive evidence that foam impact was initiating event



Wing Leading Edge Test Set Up

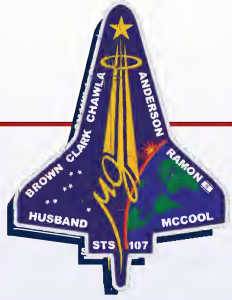






Physical Cause

- Loss of Columbia and its crew was caused by breach in the Thermal Protection System on the leading edge of the left wing.
- The breach was initiated by a piece of insulating foam that separated from the left bipod ramp of the External Tank and struck the wing in the vicinity of the lower half of Reinforced Carbon-Carbon panel 8 at 81.9 seconds after launch.
- During re-entry, this breach in the Thermal Protection System allowed superheated air to penetrate the leading-edge insulation and progressively melt the aluminum structure of the left wing
- Weakening of the structure increased until aerodynamic forces caused loss of control, failure of the wing, and breakup of the Orbiter.



Acknowledgements Regarding “Follow the TPS”

- Howard Goldstein - Retired NASA
- Don Rigali- Retired Sandia
- NASA & NASA Contractor Engineering Staff

- Larry Korb
- Mike Ehret
- Don Hendrix
- Lisa Chu-Theilbar
- James Reuther
- Greg Kovacs
- Mark Tanner
- Jay Grinstead

References:

- Follow the TPS (Arnold, Goldstein and Rigali)
CAIB Report, Vol IV, Appendix F2, August, 2003
- Aero/Aerothermal/Thermal/Structures Team Final Report
CAIB Report, Vol V, Appendix G13, August, 2003



"This cause of exploration and discovery is not an option we chose; it is a desire written in the human heart... We find the best among us, send them forth into unmapped darkness, and pray they will return. They go in peace for all mankind, and all mankind is in their debt."

President George W. Bush, February 4, 2003